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Fractal parameters of pore surfaces as derived from micromorphological data: effect of long-term management practices

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Abstract

Differences between soils in their porosity need to be quantified to diagnose changes related to management practices or to pedogenesis. Micromorphological data give abundant information on soil pore arrangement whereas fractal geometry presents tools to quantify irregular and rugged boundaries characteristic to soil pores. The objective of this work was (a) to verify applicability of the fractal scaling to irregular pore outlines revealed on soil thin sections, and (b) to test the capability of fractal parameters to reflect an influence of management practices on soil porosity. We sampled Comly silty loam soil in plots where nitrogen was supplied from conventional fertilizer sources, manure, legumes, and in uncultivated plots under grasses where no nitrogen has been supplied. Using slit-island technique, we have shown that fractal scaling was applicable to soil pore outlines revealed on thin sections. Piecewise-linear log–log relationships were found between pore area and pore perimeter. Small pores with areas less than 10^{-9} m^2 had fractal dimension D_1 between 1.06 and 1.12. Pores with areas exceeding 10^{-9} m^2 had fractal dimension D_2 between 1.42 and 1.51. The boundary between two ranges corresponded to the boundary between vughy and rounded pores. Pores with rugged fractal outlines represent 15–30% of total pore number and provide 86–98% of the total visible pore area. Management practices affected

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only the number and the area of large elongated pores. Value of D_2 was larger in samples from the legume plots than in samples from other plots.

Keywords: pore spaces; micromorphology; fractal analysis; shape analysis; soil management

1. Introduction

Soil structure is affected by long term management practices. Micmorphological data were used to quantify changes in soil structure related to cultivation and organic amendments (Kooistra et al., 1985; Dexter et al., 1983; Livingston et al., 1990; Pagliai et al., 1983, Pagliai et al., 1987; Shipitalo and Protz, 1987; Mermut et al., 1992).

Irregularity is viewed as one of essential properties of soil pore boundaries (Murphy et al., 1977; Pagliai et al., 1984; Ringrose-Voase, 1990) and of surfaces of soil peds and particles (Orford, 1981; Clark, 1981). Several methods were proposed to quantify irregularity of pore and particle outlines that reflect the pore surface roughness (Murphy et al., 1977; Orford, 1981; Ringrose-Voase, 1990)

Recent studies have shown that the irregularity of many natural boundaries obeys fractal laws (Mandelbrot, 1982). Hatano and Booltink (1992) applied a dye to well-structured clay soil and found that a fractal model described well the dependence of stained pore perimeters on pore area. Holden (1993) found that the fractal dimension can be a parameter to distinguish roughness of soil aggregates. Kampichler and Hauser (1993) successfully used photographs of soil thin sections to estimate fractal dimensions of pore surfaces from fractal dimensions of pore outlines. Fractal dimensions of soil pore surfaces reflected simulated soil degradation (Pachepsky et al., 1995).

Soil degradation or the change in soil quality because of management is a current topic of interest. Efforts were made to define soil quality and suggest a minimum set of analyses to aid in evaluating soil quality as affected by recent management practices (Doran and Parkin, 1994). Soil physical analyses recommended in the minimum data set include bulk density and water retention determinations to help define porosity of soils. Fractal dimension analysis could provide additional information by describing the shape of pores as affected by soil management practices.

The objective of this work was (a) to verify applicability of the fractal scaling to irregular pore outlines revealed on soil thin sections and (b) to test the capability of fractal parameters to reflect an influence of management practices on soil porosity.

2. Theory

The notion of fractals has been developed to describe natural objects formed either by random aggregation of, or by random subdivision into, like units over order of magnitude of scale (Talibuddin and Runt, 1994). With respect to lines, the fractal behavior means that if the length of a fixed irregular perimeter (P) is measured repeatedly in terms of the number of fixed measurement units or step length (S) required to cover the outline, then the smaller the step the longer is the apparent perimeter

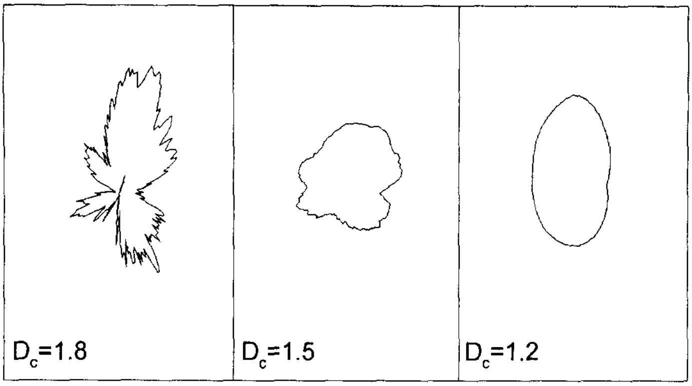

Fig. 1. Examples of single pore outlines with various fractal dimensions.

distance (Orford and Whalley, 1983). A line exhibiting fractal behavior has the perimeter and the step length related by the power law:

$$P \propto S^{D_c - 1} \tag{1}$$

where D_c is a fractal dimension. According to the fractal theory, the morphological characterization of any outline can be related to the value of the fractal dimension.

The theoretical range of D_c lies between 1.0 and 2.0 (Mandelbrot, 1982). The value of D_c reflects the plane filling tendencies of a two-dimensional outline. Examples of outlines with different fractal dimensions are shown in Fig. 1. A circle has a $D_c = 1.0$; once the outline loop is closed, no real potential exists for further filling the plane upon which the loop is lying, by the loop itself. This is true for any Euclidean polygons. The dimension of a plane is 2.0, therefore, the nearer a closed loop fills all the space of its outscribed plane, the closer to 2.0 the equivalent fractal dimension reaches.

Perimeter measurements with different step length can be done by applying dividers with various step lengths to digitized or drawn outlines. With digitized outlines, it was found difficult to keep step length equal because of varying adjacent pixel orientation (Orford and Whalley, 1983). To avoid this source of uncertainty in estimates of fractal dimensions, Mandelbrot et al. (1984) proposed the "slit-island" method. This method does not require perimeter measurements with different step length, but, instead, requires measurements of area and perimeters for the outlines varying in their size by orders of magnitude. The fractal dimension of the irregular outlines, D_c, representing either particles or pores, is included in the relationship between area A and perimeter P:

$$\alpha = \frac{P^{1/D_c}}{A^{1/2}} \tag{2}$$

Theoretically the value of α is constant within a range of sizes where the fractal scaling is applicable. In this range, D_c can be found from the slope in the regression of $\log(P)$ on $\log(A)$:

$$\log P = \frac{D_c}{2} \log A + B \tag{3}$$

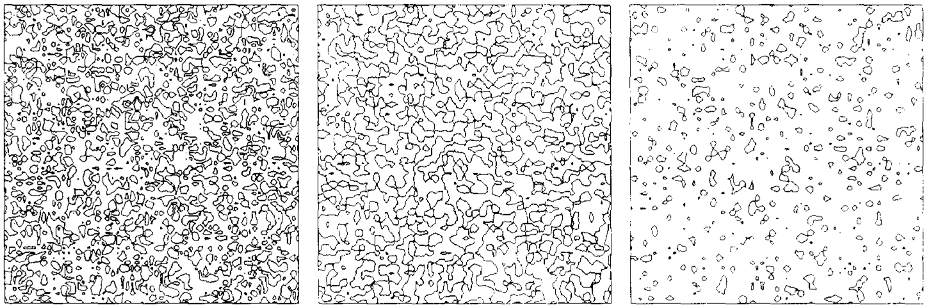

Fig. 2. Examples of multiple pore outlines with various fractal dimensions.

Fig. 2 shows how the fractal dimension reflects irregularity of multiple outlines. The larger fractal dimension is the more irregular outlines are present.

Fractal scaling is usually valid in a range of perimeter values restricted by upper and lower cutoff values. Fractal scaling with another fractal dimension may be valid outside an interval between these cutoffs (Mandelbrot, 1982; Kaye, 1994). The relationship between P^2 and A is widely used in soil micromorphology to characterize shape of pores (Murphy et al., 1977). The shape index of Swartz (1980) is a ratio

$$F = \frac{4\pi A}{P^2} \tag{4}$$

This index is used to classify pore shapes: pores are elongated or planar if $F < 0.2$ (Bouma et al., 1977; Mermut et al., 1992), pores are irregular or vughy if $0.2 < F < 0.5$ (Bouma et al., 1977) or intermediate if $0.2 < F < 0.6$ (Mermut et al., 1992), and pores are rounded if $F > 0.5$ (Bouma et al., 1977) or if $F > 0.6$ (Mermut et al., 1992). The applicability of the fractal scaling means that the shape index is dependent on the size of the pore. According to Eq. (2), the shape index can be expressed as a function of the pore area A in the following form:

$$F = \frac{4\pi A}{P^2} = \frac{4\pi A}{\alpha^{2D_c} A^{D_c}} = \frac{4\pi}{\alpha^{2D_c}} A^{1-D_c} \tag{5}$$

If the outlines are not fractal, D_c is equal to 1 and the shape index will have the same value for different pore sizes. If the outlines are fractal then $D_c > 1$, and the shape index will increase as the outlined area decreases.

Pore surface fractal dimension D_s can be estimated from a fractal dimension of pore outlines D_c. When a three-dimensional soil sample is intersected by a plane, and intersected soil pores have a fractal dimension of outlines D_c, then according to Mandelbrot (1982) this dimension is related to the fractal dimension of the pore surface D_s as

$$D_s = D_c + 1 \tag{6}$$

Therefore, the image analysis of soil thin sections can be used to estimate scaling properties of pore surfaces (Kampichler and Hauser, 1993).

3. Materials and methods

3.1. Soil samples

Samples were taken in May 1992 at plots in the Rodale Institute Research center in Kurtztown, Pennsylvania, USA. The plots represented: (1) conventional cash grain system with soybean-corn rotation and recommended fertilizers and pesticides, (2) low-input animal/grain system where the nitrogen is provided by animal manure and third year legume hay crops plowed down, (3) low-input cash grain system where the nitrogen is provided by short term legume hay and green manure crops, (4) grass strips which were not cultivated. Hereafter, the management practices are referred as conventional, manure, legume and grass strip, respectively. All plots were in experiment during 11 years. The site is described in detail elsewhere (Radke et al., 1988). The soil is a Comly silty loam with the content of particles > 2 mm in the range 8–39% and sand, silt and clay contents in the ranges between 15–25%, 58–69%, and 10–20%, respectively. Three to five undisturbed clods from 0–10 cm were taken for each management practice plot before planting. Bulk density of soil in similar clods was in the range 1.23–1.37 g cm^{-3}.

3.2. Thin section preparation

Samples having volume of approximately 50 cm^3 were placed into nalgene cups where they were air dried over several weeks. Samples were then impregnated by adding a 60:40 mixture of polyester resin : monomeric styrene, while the samples were under a vacuum. The styrene was added to lower the viscosity of the impregnating liquid. A fluorescent dye (Uvitex by Ciba-Geigy) was added to the impregnating resin at a rate of 1 g L^{-1}. Samples were left uncovered in a fume hood for two weeks, after which the nalgene cups were covered. The samples were hardened by exposing them to gamma radiation. A dose of approximately 5 MRad over 24 hours was sufficient to cure the resin so that polished blocks could be prepared. One cm thick blocks were cut to have an exposed surface of approximately 3 cm $\times$ 5 cm. One surface from each block was polished with adhesive backed grinding disks, using progressively finer grit size and an oil-based lubricant. Final polishing of the blocks with #600 grit was sufficient to produce clear photographic images. Photographic images were made using a high contrast black and white film while illuminating the polished blocks with UV light source, in an otherwise darkened room.

3.3. Quantifying porosity

To measure length, breadth, area and perimeter of pores distinguishable in photos, Quantimet-917 image analysis system based on DEC PDP-11 was used with video camera having 500,000 pixels resolution. The image was sampled from 35 mm negatives. Each frame was divided in four subsample areas.

3.4. Estimating parameters of fractal models

There are two possible ways to look at the data on pore geometry that we have obtained. One way is to consider each thin section as a replication and to look at values of fractal parameters averaged over these replications. Another approach is to collect the data on pore geometry for all samples of soil under particular management and to treat these collections as mixed samples representing the management. We have applied both approaches.

Based on data presented below, we have assumed that there will be two intervals of radii over which values of D_c are constant. A modified Marquardt algorithm (Van Genuchten, 1981) was used to fit piecewise linear regression equations to data and to estimate standard errors of parameters. Availability of the standard errors of the parameters enabled us to use Student's *t*-test to check the statistical hypothesis on equality of average parameter values, assuming measurement errors to be normally distributed.

4. Results

Statistical distributions of measured pore outline perimeters are shown in Fig. 3a. About 15% pores have the same smallest perimeter value 3.87×10^{-2} mm. The probability of finding a pore outline with the large perimeter is higher in samples from grass strip plots and legume plots than in samples from conventional and manure plots.

The probability distribution of the outlined area is shown in Fig. 3b. About 10% of

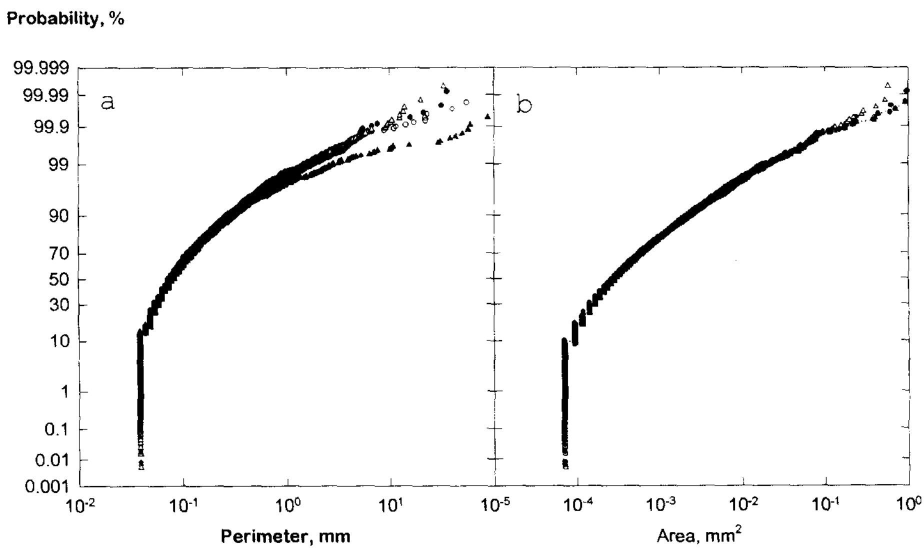

Fig. 3. Probability distrubution functions of pore outline perimeter (a) and the outlined area (b); (○) legume, (●) manure, (△) conventional, (▲) grass strip.

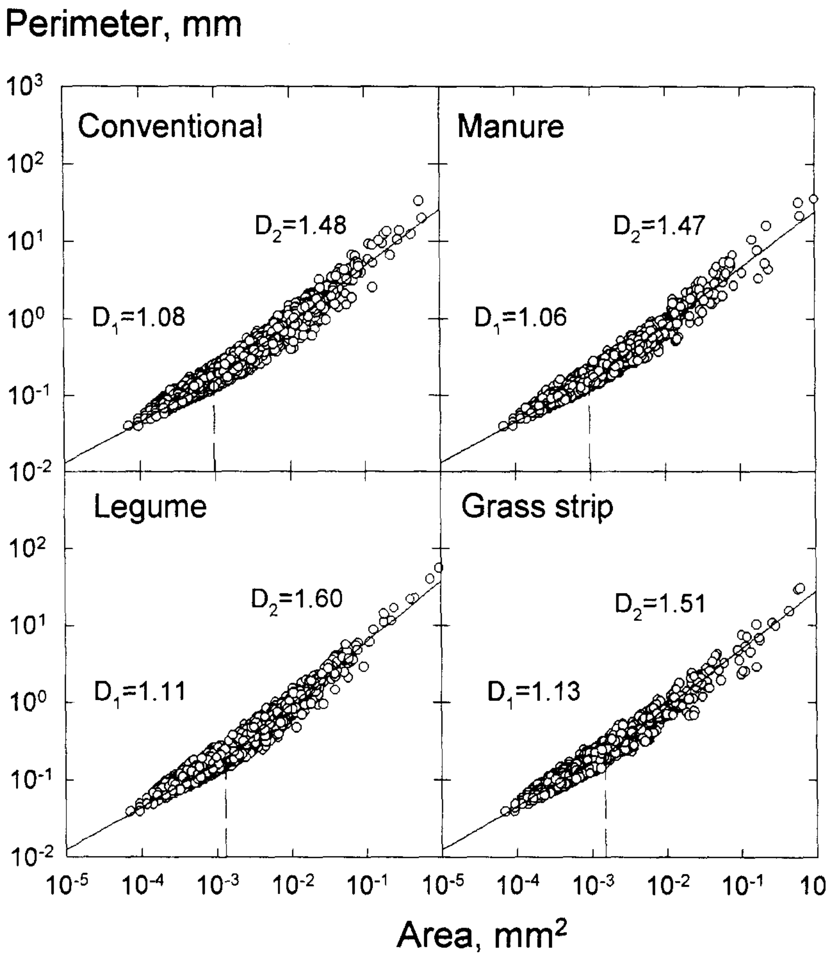

Fig. 4. Dependencies of pore outline perimeter on the outlined area for samples from all plots.

pores have the same smallest area value 7.03×10^{-5} mm^2. Differences between the samples from legume, conventional and manure plots are small. The probability to find a pore with the large outlined area is larger at grass strip plot than at other comparison with manure, conventional, and legume plots.

Dependencies of pore outline perimeter P on outlined area A are shown in Fig. 4. For all management practices, the dependencies display two intervals of linearity. Smaller pores have the slope of the log(P)–log(A) dependence close to 0.5, i.e., $D_c \approx 1$ and (perimeter)^2 : area ratio does not depend on the pore size. Larger pores form another segment of linearity with the slope markedly larger than 0.5 and D_c is between 1 and 2. In this range of pore sizes, pore outlines exhibit fractal behavior, and the ratio P^2/A increases as the pore size increases. The cutoff area A_c which marks the boundary between the linear intervals is about 10^{-3} mm^2.

One possible way to analyze these data is to assume that the irregularity of the

Table 1
Fractal parameters of pore outlines estimated using "slit island" method for soil samples from different management practices. Within a row, values with different letters are significantly different at $p < 0.05$

Parameter	Management practice			
	Conventional	Manure	Legumes	Grass strip
Estimated from replicated thin sections				
Fractal dimension D_1	1.075a (0.010) [a]	1.064a (0.022)	1.110a (0.015)	1.117a (0.027)
Fractal dimension D_2	1.458a (0.047)	1.471a (0.037)	1.589b (0.028)	1.472a (0.067)
Cutoff pore area $A_c \cdot 1000$, mm^2	0.942a (0.141)	1.061a (0.199)	1.254a (0.102)	1.331a (0.445)
Perimeter at cutoff P_c, mm	0.149a (0.013)	0.157a (0.020)	0.183a (0.037)	0.192a (0.045)
Estimated from collections of all pore data				
Fractal dimension D_1	1.084a (0.005) [a]	1.064b (0.004)	1.114c (0.004)	1.131dc (0.007)
Fractal dimension D_2	1.482a (0.006)	1.470ac (0.007)	1.603b (0.007)	1.504ac (0.010)
Cutoff pore area $A_c \cdot 1000$, mm^2	0.965a (0.025)	0.970a (0.030)	1.315bc (0.033)	1.501c (0.098)
Perimeter at cutoff P_c, mm	0.153a (0.003)	0.153a (0.003)	0.188bc (0.003)	0.207c (0.009)
Coefficient of determination	0.988	0.988	0.990	0.988
Mean square error	0.055	0.053	0.054	0.063

[a] Standard error is shown in parentheses.

outlines of small pores can be revealed with the resolution used. Then the first interval of linearity has to be characterized by its own fractal dimension of the outlines D_1 that has to be found together with D_2 and A_c. Another way of the data analysis is to assume that irregularity of outlines of small pores cannot be seen and the scaling dimension of pore outlines is exactly 1 for the small pores. Then the fractal dimension of the second linearity interval D_2 and the cutoff area A_c are the two fractal parameters to find. We have applied both methods and will discuss results below.

The assumption that both linearity intervals are fractal leads to the results shown in Table 1. For each management practice, fractal parameters were found separately for each replicated thin section and then from all data collected from thin sections of this management practice. For each management practice, when fractal parameters from replicated thin sections were averaged, there was no significant difference between these mean values of parameters (the upper part of the Table 1) and estimated fractal parameters from all data (the lower part of the Table 1). Standard errors obtained from collections of all data were used for the statistical comparisons presented below.

Values of D_1 are in the range from 1.06 to 1.13 and values of D_2 are in the range from 1.42 to 1.51. Fractal dimension D_1 is significantly larger in samples from the legume and the grass strip plots than in samples from conventional and manure plots. Value of D_2 is significantly larger in samples from the legume plots than in samples from other plots. Cutoff area values, A_c, are significantly larger in samples from the legume plots and grass strip plots than in samples from conventional and manure plots.

The assumption that the scaling dimension is equal to 1 in the interval of smallest pores leads to the results shown in Table 2. Here we estimated only fractal dimension D_2 for the interval of larger pores and cutoff pore area values. No significant differences were found between fractal dimensions of pore outlines in samples from conventional,

Table 2
Pore outline fractal parameters estimated for soil samples from different management practices using "slit island" method and assuming the fractal dimension of the smallest pore range to be 1. Within a row, values with different letters are significantly different at $p < 0.05$

Parameter	Management practice			
	Conventional	Manure	Legumes	Grass strip
Estimated from replicated thin sections				
Fractal dimension D_2	1.422a (0.032) [a]	1.424a (0.012)	1.503b (0.016)	1.418a (0.042)
Cutoff pore area $A_c \cdot 1000$, mm^2	0.581a (0.058)	0.643a (0.028)	0.614a (0.024)	0.506a (0.093)
Perimeter at cutoff P_c, mm	0.110a (0.006)	0.115a (0.002)	0.115a (0.012)	0.104a (0.010)
Estimated from collections of all pore data				
Fractal dimension D_2	1.443a (0.005)	1.438a (0.006)	1.512b (0.005)	1.431a (0.007)
Cutoff pore area $A_c \cdot 1000$, mm^2	0.592a (0.010)	0.660b (0.014)	0.618ac (0.010)	0.517d (0.019)
Perimeter at cutoff P_c, mm	0.112a (0.001)	0.117b (0.001)	0.115bc (0.001)	0.106d (0.002)
Coefficient of determination	0.988	0.988	0.989	0.988
Mean square error	0.055	0.054	0.055	0.065

[a] Standard error is shown in parentheses.

manure and grass strip plots. Samples from the legume plots had fractal dimensions markedly larger than other samples. The cutoff area was the smallest in samples from the grass strip plots. Perimeters at cutoff were much closer to each other than in Table 1. The same is true for cutoff pore area.

Relative total number and total area of pores with outlined area greater than the cutoff area A_c are shown in Table 3. Pores with fractal outlines represent 15–30% of total pore number but provide 86–98% of the total pore area.

Assuming pores at cutoff having a shape of an ellipse, one can calculate a capillary potential below which the pore will be emptied. Values of cutoffs shown in Table 1 correspond to capillary potentials circa -20 kPa.

Shape index values calculated from Eq. (5) at the cutoff boundary between two intervals of linearity are presented in Table 4. Values of $F_c = 4\pi A_c / P_c^2$ are very close to 0.6 when the absence of fractal scaling and $D_1 = 1$ were assumed for smaller pores.

Table 3
Relative total number and relative total area of pores with areas greater than the cutoff area A_c for soil samples used in this study

Parameter	Management practice			
	Conventional	Manure	Legumes	Grass strip
D_l estimated together with D_2 and A_c				
Relative total number	0.21	0.20	0.16	0.15
Relative total area	0.86	0.87	0.86	0.96
D_l set equal to 1				
Relative total number	0.31	0.27	0.30	0.33
Relative total area	0.91	0.90	0.92	0.98

Table 4
Shape index calculated at the cutoff boundary between two intervals of linearity of log P–log A dependence

Method of estimating D_l	Management practice			
	Conventional	Manure	Legumes	Grass strip
Set equal to 1	0.59	0.61	0.59	0.58
Estimated together with D_2 and A_c	0.52	0.55	0.47	0.43

Value of $F = 0.6$ is defined as the boundary between rounded and intermediate pores as defined by Mermut et al. (1992) and the cutoff separates pores of these two classes.

When the fractal scaling was assumed to be applicable in the interval of small pores, values of F were about 0.5 at the cutoff boundary (Table 4). The cutoff boundary corresponded to the boundary between vughy and rounded pores as defined by Bouma et al. (1977). Values of the shape index depended on pore area. A consequence of Eq. (5),

$$\frac{F}{F_c} = \left(\frac{A}{A_c}\right)^{1-D_l} \tag{7}$$

has been used to calculate F for area values, A, different from A_c. Values of F increase as the outlined area decreases according to Eq. (7), and for all management practices, they are equal to 0.65 for the smallest of observed pores with area $A_{min} = 7.03 \times 10^{-5}$ mm^2. Therefore, the smallest of observed pores are rounded.

5. Discussion

5.1. Applicability of the fractal scaling model to pore boundary irregularity

Results presented in Table 1 and in Table 2 show that the fractal scaling is a reasonable model to describe data on the relationship between pore outline perimeter P and outlined area A. The correlation coefficients between calculated and measured log P lie between 0.988 and 0.990. Mean square errors of regressions log P on log A are in the range between 0.055 and 0.065. This range corresponds to 13–15% mean square relative error of the estimates. Kampichler and Hauser (1993) also found a good correlation ($r^2 = 0.92$–0.93) between pore area and pore perimeter in their samples.

Micromorphological data of other authors imply the applicability of the fractal scaling. For example, the dependence of the shape index on the pore area as predicted by the Eq. (7) means that the larger is a pore in the collection of pores with fractal surfaces, the more probable that the pore is elongated or planar and the less probable that it is rounded. This kind of shape–size relationship has been found by several authors (Murphy et al., 1977; Mermut et al., 1992). Dependence of the shape index on the pore area makes this index highly variable when a range of pore sizes is being observed. This can explain high variability of the shape index in comparison with other parameters in Kubiena size soil samples studied by Puentes et al. (1992).

5.2. Fractal scaling and pore shape

Fractal scaling does not distinguish pore shapes. Pore classifications often invoked various shape-indicating categories like fissures, packing pores/vughs, channels, etc. Ringrose-Voase (1987) compared two interpretations of image pore analysis data, one with combined parameters for fissures and packing pores and another with parameters for fissures and packing pores kept separately. He found that combination of parameters is more realistic because in reality the shape of pore space changes continuously throughout its extent. He concluded that in absence of sharp boundaries between pore types the imposition of a classification is not strictly correct, and that a basic type of pore geometry seem to be remarkably similar over a wide range of scales. These observations based on the large volume of data support applications of fractal scaling in quantification of pore outlines.

Fractal models provide scale-independent parameters of the pore boundary irregularity. Other methods to characterize irregularity are based on scale-dependent parameters. For example, Murphy et al. (1977) distinguished two separate aspects of pore outline irregularity: the digitation and the crenulation. Digitation was expressed by the length of protuberances away from the main part of the void. Crenulation referred to density of small protuberances at void edges. Authors mentioned that crenulation changed with magnification, and new irregularity details could be seen after each magnification.

5.3. Possible reasons of the piecewise linear "perimeter–area" dependencies

The reason of two intervals of fractal behavior remains to be revealed. Kampichler and Hauser (1993) found only one range of linearity for the $\log(P)$–$\log(A)$ relationship. These authors studied area–perimeter relationships for pores with areas larger than the threshold value 3×10^{-3} mm^2 which is larger than the cutoff area values found in our study (Table 3).

Frequency distributions both of outlined area and of a pore outline perimeter in our samples are similar to distributions found by other authors who used Quantimet. The distributions are asymmetrical. Rounded pores with area less than A_c outnumber larger pores but account only for 2–14% of total area. Similar proportions were described by Mermut et al. (1992) and Bullock and Thomasson (1979).

The resolution of the Quantimet may be not sufficient to register fine irregularity of soil particle surfaces. Then the results of observations will be a textural fractal as described and discussed by Kaye (1994). Creating agglomerate of perfectly circular subunits led to a fractal structure with two distinct fractal intervals with different fractal dimensions. In this case, the assumption $D_1 = 1$ is valid. Indications that it may be the case are both the similarity of cutoff perimeter values in Table 2 and the similarity of the cutoff shape index in Table 4. Yet another possibility is that the small pore scaling we observed is real and not induced by the resolution of measurements. We plan to carry out a separate study to find causes of two-interval scaling patterns shown in Fig. 4.

5.4. Which pores are affected by the management practices?

In our study, management practices affected only the number and the area of large elongated pores. Outlined area distribution curves shown in Fig. 3b coincide up to 95%

probability. The difference can be found only in the range of large pores with area > 0.004 mm^2. Here the shape factor calculated from Eq. (7) is between 0.23 and 0.28 in samples from conventional, manure, legume, and grass strip plots. Only the number and the outlined area of largest pores that are planar or close to planar may be influenced by the management practice as it was in the study of tillage effect by Mermut et al. (1992). Tillage had similar effect on the outlined area of pores of different shapes in studies presented by Mermut et al. (1992). The authors found that the aerial porosity of pores that were not planar ($F > 0.2$) was not affected by the tillage method. Average pore radii at a cutoff are in the range 0.015 to 0.025 mm. These radii correspond to soil capillary potential -20 kPa at the cutoff between two ranges of scaling which is close to the capillary potential at field capacity. Therefore, between-management differences in soil porosity scaling are found mostly for pores that are usually air-filled and serve for the redistribution of precipitation. This part of the pore space is referred as macroporosity (Germann and Beven, 1981) or as macro- and mesoporosity.

5.5. Possible reasons and consequences of the observed differences among soil pore spaces

Results of this study and available literature allow us to hypothesize about relation between soil management practices and soil porosity. The organic matter composition may be one of the reasons of differences between legume and manure treatments. This would correspond to the observation of Fortun et al. (1990) who found that fulvates and humates from manure caused a closing of planes and a formation of larger aggregates, whereas fulvates and humates from peat increase vughs and smaller aggregates. Differences in structures of root systems between legumes and cereals might be a source of differences between fractal dimensions in samples from the legume plots and in samples from other plots. This could concur with observations on relative size and shape in roots of those plants (Petrie et al., 1992). Finally, one might assume that the pore arrangement mirrors arrangement of particles into aggregates and that the increase in proportion of large aggregates might explain the relative increase in number of large pores. Then our results would corroborate observations of Rasiah et al. (1992) on fractal scaling of soil aggregates as affected by soil management.

Transport of water and gases in soils should be affected by differences in the arrangement and number of pores. Given the same area, perimeters of large pores under legumes are larger than under other systems, and given the same perimeter, the number of large pores is greater at the legume plots than at other plots. This probably induced differences in infiltration rates reported by Peters et al. (1992) for the same plots. The authors found that soil at the legume plots had the largest infiltration rate, whereas soil at conventional plots had the lowest infiltration rate. Gas transport is also affected with the availability of large pores. Sikora et al. (1996) observed significantly larger microbial respiration at the legume plots than at conventional plots in the same experiment. This may be caused partly by the better gas exchange at these plots.

The available habitat for soil microorganisms is affected by the number and arrangement of pores. Pores with areas larger than the cutoff that we found are referred as pores important for the soil micro-arthropodes population (Kampichler and Hauser, 1993). The authors pointed out that variations in the fractal dimension may result in variations in the available habitat for these species. The higher the fractal dimension is, the steeper will be size–abundance distribution of microarthropodes.

The legume plots that had the highest fractal dimension had the most favorable combination of transport processes and biological transformation processes. Yakovchenko et al. (1996) estimated nitrogen use efficiency to assess soil quality in the farming system trial that included sampled plots. The legume plots had the highest nitrogen efficiency and lowest nitrogen loss among studied systems.

It remains to be seen whether the fractal dimension of pore boundaries can be a reliable indicator of transport and transformation process rates. This question presents exciting horizons to explore.

6. Conclusion

Fractal scaling was found applicable to irregular pore outlines revealed on soil thin sections. The slit-island method provided reliable parameter values for the fractal model. Fractal scaling results in dependencies of the pore shape factor on pore size found by other authors who quantified micromorphological data obtained from thin section images. Fractal dimensions of pore outlines were close to 1 in small pores and were circa 1.5 in larger pores. The cutoff between two fractal intervals was between pore radii 0.02–0.03 mm. Fractal scaling with fractal dimensions substantially larger than 1 was found for pores that are elongated or planar, and irregular or vughy or intermediate. For these pores, no significant differences were found between fractal dimensions of pore outlines in samples from conventional, manure and grass strip plots whereas samples from the legume plots had markedly larger fractal dimensions.

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